Constructing the 3496Hz "D-Q" Beacon Receiver

***Brian Pease** provides constructional details for his "double quadrature" receiver which is used in conjunction with his radio-location transmitter.*

Introduction

This article gives theoretical and constructional details for a simple high performance 3496Hz long range cave radio beacon receiver which uses what I call a "Double Quadrature" detector. It is used to receive either a steady (non-pulsed) beacon signal for determining location and depth or CW (Morse Code) for passing information to the surface. The complementary beacon transmitter has previously been described in this *Journal* (Pease, 1996a).

A conventional loop antenna is used to locate "ground-zero". Searching can be aided by signal strength readings. Once ground-zero is located, depth may be measured by the traditional "null-angle" method and/or by reading the signal strength on a digital voltmeter followed by a simple calibration on the surface after the trip. Alternately, the "ratiometric" method (Gibson, 1995, 1996) involving the ratio of two strength readings taken at different heights above the surface. These last methods have allowed a complete "search – locate ground-zero – find depth" sequence to be completed in five minutes by one person on the surface for depths of 50 feet in open terrain. This can result in a happy in-cave crew if a voice down-link is used.

Receiver sensitivity is limited only by the thermal noise of the loop, which will be overcome by atmospheric or power line noise much of the time. If needed, the narrow 1Hz filter has 30dB of attenuation only 17Hz either side of the 3496Hz carrier frequency, which suppresses 60Hz power line interference. 3496Hz is not a good frequency for the UK due to a very close harmonic of 50Hz. The operating frequency can be easily changed if desired. Direct measurement of the H-field strength is also possible.

Knowledge of the conductivity of the rock can be used to improve the accuracy of the depth measurement for depths over 30-40 metres (Pease, 1991; Drummond, 1989). By placing both the beacon and receiver on the surface, a simple "depth-of-null" measurement allows easy rough estimation of average ground conductivity for any (approximate) depth.

Specifications

Theoretical ultimate range of this receiver (using headphones for searching) with my beacon with its small 2-foot diameter loop is 885 metres in "free space" assuming coaxial loops, 1Hz bandwidth, 10dB s/n ratio, and no atmospheric or power line noise. The "real world" range may be quite a bit less, however the PLL and DC meter will work *below* the noise in the 1Hz bandwidth.

Measured Specifications (12V DC)

- Sensitivity (equivalent noise H field) is 1.3nA/metre in a 1Hz bandwidth.
- Sensitivity of the rf amplifier (noise at input) is 20nV in a 1Hz bandwidth.
- Bandwidths are 1Hz and 32Hz at the -3dB points.
- Selectivity is 12Hz at -20dB points in 1Hz mode.
- Loop parameters:
  Q=29 (25 with electrostatic shield)
  Resonant impedance = 125kΩ (215kΩ with 2nd LC circuit)
  Thermal noise = 54nV/1Hz bandwidth with 2nd LC circuit
  E-field effective height = 0.12 metres
- Phase-locked loop bandwidth (-3dB) is 0.16Hz.
- PLL capture (lock) range is 0.14Hz.
- Threshold for phase-lock is about 3mV on the DC DVM.
- Threshold for the lock indicator/alarm is about 60mV on the DC DVM
- Maximum rf linear rf amplifier output is 2.75V rms.
- Maximum DC meter reading is approximately 1V DC without rf overload.
- Maximum AC meter reading is approximately 2V rms without rf overload.
- DC meter bandwidth (-3dB) is 0.15Hz with 10μF.
- Settling times: The receiver takes about 2 minutes to stabilise at turn-on. The DC meter takes 10 seconds to settle fully with 10μF.
- Power: Draws about 35mA from two 9V alkaline batteries in series, which will give several hours of life.

Circuit Description

The Loop Antenna

A previous article (Pease, 1996b) gives a more detailed circuit description than presented here. That article also included the block diagram. The loop antenna consists of one pound (450g) of #29 awg (0.286mm[1]) enamelled wire wound 18.25" (464mm) in diameter (I got 430 turns), wrapped with electrical tape and mounted on a board. I covered the winding with a (probably unnecessary) electrostatic shield.

The second tuned circuit (L1 and C35, overleaf) reduces rf amplifier overload from nearby transmitters and power lines, but should not be needed in most situations. The loop is resonated with a 1000pF Arco trimmer plus polystyrene and/or silver mica capacitors. The thermal noise of this antenna determines the maximum sensitivity of the receiver.

The RF Amplifier

The rf amplifier (U0 & U1) has been upgraded to a 3-stage design with a high impedance input using FET-input op-amps and a unique wide range gain control (R22) which varies the gain of U0 and U1A together. Counting the 40 dB input attenuator the gain can be varied from -4 to +100dB. The circuit has low input noise compared to the thermal noise of the loop.

An rf overload LED (D6) utilises an Exclusive-OR (XOR) gate to indicate saturation of the rf amplifier by atmospheric noise, power line EMI, or the beacon signal. The circuit was empirically designed but the prototype works fine.

The Local Oscillator

The local oscillator (U6) uses a common 3.579545MHz NTSC colour burst crystal which is binary divided in U6 to the 3495.65Hz carrier and 437Hz audio tone frequencies. It is tuned to match the beacon frequency closely.

XOR gates U7 A & B provide the 90° phase shifts required by the detector. If a different crystal frequency is chosen then the band-pass filter (U3B) must be changed since the audio frequency will no longer be 437Hz.

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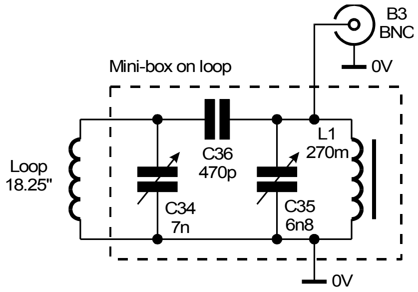
[1] Nearest metric size is 0.28mm. Nearest Imperial size is 31 swg (0.295mm) or 32 swg (0.274mm).



Schematic of Optional Filter

The Double-Quadrature Detector

The narrow band frequency converting detector in this receiver is an improvement on the 8-pole commutating filter/mixer (my idea) used in Ray Cole's "Organ Cave Radio" (Cole, 1985, 1986; Stevens, 1988). It was built to solve the operational problems of my "synchronous" receiver which was used for earlier location, depth, and conductivity measurements (Pease, 1991).

This detector uses a 2-channel in-phase/quadrature direct conversion mixer (U5A & B) whose DC (base-band) outputs are low pass filtered and then up-converted (by U5C & D) to a pair of audio tones whose algebraic sum is proportional to signal strength. The great selectivity results from the fact that the 1Hz bandwidth mode rolls off at -20 dB per decade based on the 0.5Hz bandwidth of the RC filters (R1, C1, C3 and R2, C2, C4). Without the PLL the DC outputs of the two low pass filters would drift slowly with time (one is maximum when the other is zero) but in theory their rms sum will remain constant. In practice there is about 1dB variation which is inaudible but is annoying for field strength measurements. The combination of the second mixer stage, summer (U3A), and 437Hz band-pass filter (U3B) provide an audio output and allow signal strength measurement with an ordinary AC DVM. The output remains a sine wave even when the input is seriously overloaded which more or less eliminates the need for AGC, limiters, or log amplifiers while searching for ground zero.

The Audio Amplifier

The audio amplifier in the prototype was just a conventional non-inverting op-amp designed for use with my 2kΩ high efficiency headphones. For the usual low impedance (8-30Ω) stereo phones a better amplifier is needed so I designed the LM-386 circuit shown (U9). The new circuit may be more prone to feedback due to the higher currents involved.

The Phase-Locked Loop

A phase-locked loop can be easily added to the D-Q detector to solve the drifting problem by locking the receiver's local oscillator to the beacon. The PLL's main purpose is to improve the signal strength readout by allowing the use of a DC meter. It also allows for a "lock alarm" that will alert the operator when a signal is present. It has no other effect on normal receiver operation.

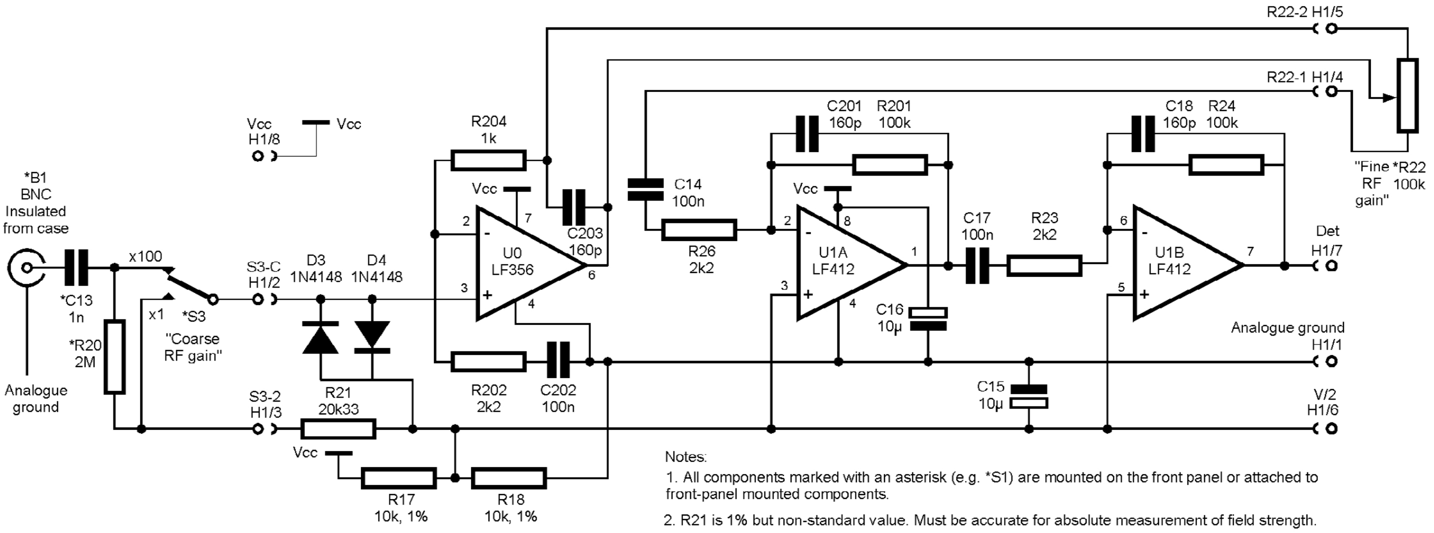
The base-band signal from one channel of the D-Q detector is connected to the input of the high gain DC coupled amplifier U4A (+60dB) whose output drives variable capacitance diode V1 which can slightly shift the frequency of the 3.57 MHz crystal. The total shift at 3496Hz is only 0.14Hz but this is more than enough. Once locked, the SIN (quadrature) signal is nulled out while the COS (in-phase) channel carries a steady DC voltage proportional to the beacon signal. Extremely narrow loop filtering allows the PLL to lock on signals that are well below the noise and interference in the receiver's 1Hz bandwidth and to give a steady readout on a DC DVM. The DC meter has two desirable features: 1) There is an inherent 3dB improvement in s/n ratio over the AC DVM (for the same receiver and meter bandwidth) since the DC meter only sees noise from one channel and 2) the DC bandwidth can be narrowed with a simple RC low-pass filter almost without limit to steady the readout. R38 & C33 give a bandwidth of 0.15Hz for an additional 8 dB improvement in s/n ratio. This steady (positive polarity) reading is the best proof that the receiver is phase-locked. In poor conditions, the DC readout is superior to the AC meter, although neither exhibits "drift" while the receiver is locked. My prototype has a built-in digital panel meter that shares the receiver's power source, but requires a differential amplifier to isolate the grounds.

Lock Indicator and Audio Alarm

To make waiting on the surface less boring I added a circuit to indicate when the receiver phase-locks on a beacon. U8B is an op-amp integrator with a differential input that monitors the base-band (DC) output of both channels. When the in-phase channel rises a few millivolts (positive) above the quadrature channel and holds for several seconds, the integrator output will rise high enough to trip XOR gate U7D and light the "locked" LED and sound a loud alarm if desired. Its threshold is set higher than the minimum PLL lock-on signal in order to reduce false alarms. It is not foolproof but it has worked fine in field tests so far.

Construction

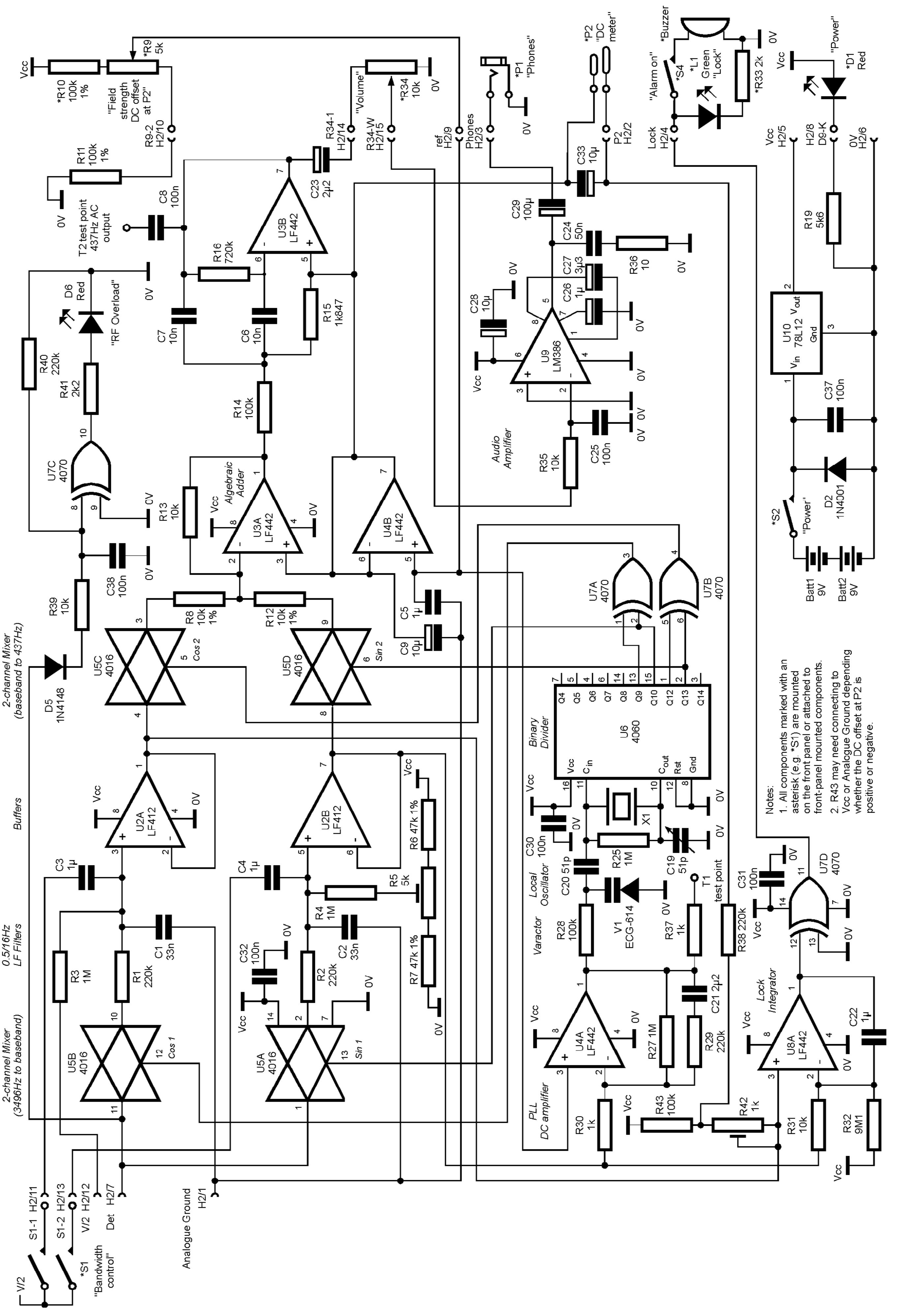
Ian Drummond laid out a 3-part printed circuit board containing the beacon, original receiver rf amplifier, and receiver. Four boards were made and three are actually working. We may offer some updated boards for sale if there is enough interest. I plan to construct an experimental 874Hz receiver with my board since my prototype 3496Hz unit works just fine.



Notes:

1. All components marked with an asterisk (e.g. *S1) are mounted on the front panel or attached to front-panel mounted components.
2. R21 is 1% but non-standard value. Must be accurate for absolute measurement of field strength.

Schematic of RF Amplifier Board



Notes:

1. All components marked with an asterisk (e.g. *S1) are mounted on the front panel or attached to front-panel mounted components.

2. R43 may need connecting to Vcc or Analogue Ground depending whether the DC offset at P2 is positive or negative.

Schematic of Main Board

For this receiver to work properly, digital noise, especially the 3496Hz local oscillator signal, must be kept out of the analogue circuits, particularly the rf stage, otherwise adjusting the rf gain will affect the detector null. With the PLL circuit, any 3496Hz or sub-harmonic leakage may cause "lock-up" on the receiver's own local oscillator signal at high rf gain settings and possible variation in accuracy at different gain settings. The entire radio must be shielded to prevent feedback to the loop antenna. I don't know if the loop's electrostatic shield is necessary, but I do get extremely deep nulls at close range (>70dB) and have no "hand" effects. The second tuned circuit (if used) should be shielded and mounted on the loop to isolate it from the digital circuitry. I can place my 2kΩ headphones and the entire receiver, at maximum rf and audio gain, into the centre of the loop without feedback or noise of any kind.

I built the rf prototype amplifier on its own Radio Shack board and shielded it, along with the input connector (which is not grounded to the case), attenuator, and rf gain control, from the rest of the receiver. The bypass capacitors for $+V_{CC}$ and V/2 (C15 & C16) are also included. I used a ten turn potentiometer with calibrated dial for rf gain. As a precaution, all analogue grounds are brought individually to a single ground lug bolted to the partition separating the rf amplifier from the main board. Oscillation is always a potential problem with 100dB gain. I placed a shield of grounded foil between the input circuits (B1, S3, etc.) and the rf amplifier circuit board to eliminate some obvious feedback at maximum gain. I also used a very short coax to connect pin 3 of U0 to the input circuits, with the shield connected only at the input end.

The layout of the main board is not critical except to keep digital signals away from the audio amplifier. Again, in the prototype all analogue grounds are brought individually to a lug on the same bolt holding the rf amplifier ground lug. The prototype used an RS 2 × 3 × 5 inch (50×75×125 mm) aluminium mini-box for overall shielding and a belt clip for hands-free operation. Ian's custom PC boards require a larger box.

If the PLL circuits are not being installed then C20 is replaced by a 30pF capacitor connected from pin 11 to ground. V1 along with all parts associated with U4A, U7D, U8B, and the DC DVM output are not installed.

The D-Q detector circuit must be carefully adjusted to null out the 437Hz tone (when no signal is present). If the PLL is not installed then you may have to replace R8 & R12 with a pot to equalise the gain in the two channels to minimise fluctuations in the AC output level when drifting phase causes the signal to shift from one channel to the other. I put the "null" control (R9) on the front panel with a knob and the "null balance" pot (R5) on the circuit card but accessible from outside with a screwdriver. "Null balance" should only need touching up once or twice a day when temperature changes. It will pay to use 1% resistors (or matched pairs) for all three DC divider networks. The actual values are not critical. The "null balance" pot should be centred before installation to aid in the initial tune-up.

The receiver will work directly from a single 9V battery without a voltage regulator if desired, but there will be significant drift of the null as the voltage drops along with small changes in gain.

Initial Tune-up

1. If the PLL circuit is installed, break the loop by removing the 100kΩ resistor (R28) from pin 1 of U4A and connecting it to V/2.
2. Turn on the receiver while monitoring current drain from the battery. Mine is 35mA at 12V DC. Do not connect the antenna.
3. Check all three voltage divider circuits for a nominal value of ½ the supply voltage.
4. The output of each op-amp should also be about ½ of the supply voltage. If the PLL circuits are installed, the output of U4A is acceptable if it is within 1-2V of V/2 and varying.
5. You should hear a 437Hz tone in the earphones. With the rf gain switch in the "low" position and the rf gain control at minimum, alternately adjust "null" and "null balance" controls until a deep null is found, leaving only noise. If you run out of adjustment range, it may be necessary to trim one of the voltage divider resistors.
6. Now put the rf gain switch in the "low" position and the rf gain control to maximum. The output noise level should increase, especially in the 32Hz bandwidth mode. Now connect the antenna.
7. Tune up the loop tuned circuits by using your beacon signal while monitoring the AC output of the rf amplifier directly (if possible). Keep rf amplifier output below 1 volt rms to avoid saturation. The 437Hz audio tone will be steady if both channels are working. With the beacon off, in the 1Hz mode at high rf gain you should now be able to detect individual lightning strikes. Atmospheric noise is loudest at night and least in the morning. It is also loudest in the summer and least in the winter.
8. Match the receiver to the beacon frequency by first receiving a fairly strong beacon signal. If the PLL circuits are installed simply monitor test point T1 with an *analogue* DC voltmeter while adjusting C19 to lower the beat frequency as close to zero as possible. Without the PLL circuits, monitor one of the DC outputs of U2 or temporarily disconnect R8 and monitor "pulsing" audio.
9. Reconnect R28 and/or R8. A receiver with PLL should lock on the beacon signal. C19 can be touched up to "centre" the voltage at test point T1 at V/2. The lock LED L1 (not to be confused with the coil L1) should light. The sensitivity of the lock indicator is adjusted by R32. Raising its value increases weak signal sensitivity but will increase false triggering from noise at high rf gain.
10. A small "offset" will exist between the audio and DC DVM nulls with the receiver adjusted as in step 5. Adjust R42 to null the DVM. It may be necessary to move the connection of R43 from B+ to the analogue ground to make this adjustment depending on whether the offset is positive or negative.

Calibration of the rf gain controls and "absolute" calibration is beyond the scope of this article. Calibration of the controls is necessary for measuring conductivity as the relative strengths of a peak and a deep null must be recorded. Absolute calibration allows depth by field strength to be measured in "real time" and allows one calibration point to be used for widely different depths. No calibration is necessary for the "ratiometric" method of depth measurement as the two numbers will always be similar enough to be recorded without changing the gain settings.

Operation

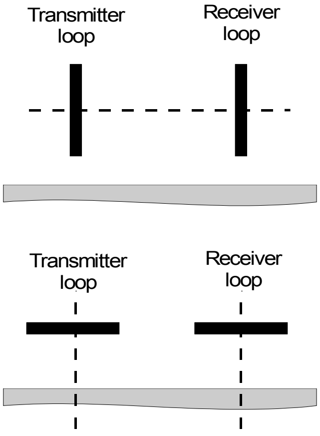
General

After several minutes' warm-up, I carefully null the receiver, using both null controls, at minimum rf gain and without the antenna. The front panel null control will need adjustment occasionally during the day using the same procedure. With the PLL receiver I just set the loop on the ground; turn on the alarm; switch to 1Hz bandwidth; and then increase the rf gain as much as possible without false alarms. I am then free until the alarm sounds when the continuous beacon signal comes on. If the signal is strong I will use the wide bandwidth mode while searching due to its faster reaction time.

Depth by Null Angle

The details of locating a ground-zero and measuring depth by the "null angle" method have been given too many times to repeat here. I use a table giving depth-to-horizontal distance ratios for each 0.5° of loop tilt from vertical (Pease, 1997b). Null angles of 25° to 40° from the vertical should give the best results. With this receiver one has the option of measuring the relative strengths of the horizontal and vertical fields separately and calculating the null angle as an arc-tangent. This seems to give more accurate results than direct measurement when the null is very shallow (<20 dB).

Depth by Absolute Field Strength



Loop Geometry
Top: Coaxial (loops on edge)
Bottom: Horizontal (loops on side)

In its simplest form, depth-by-absolute-field-strength requires calibrating the beacon and receiver on the surface after the trip. It also requires some sort of rigid frame for the beacon loop. After locating ground-zero, set the receiver's loop horizontally on the ground and switch to the 1Hz mode. Connect the DC DVM and set the rf gain controls so that the rf overload LED does not light. Record the maximum reading and the exact rf gain and switch settings. Later, set up both loops coaxially on the surface as shown in the illustration on this page. With this geometry the ground has little effect on the signals (at moderate spacing over limestone anyway) so the result will be close to the free-space value. Use the same receiver settings recorded earlier. Now simply adjust the spacing to duplicate the reading obtained at ground zero and measure the distance to obtain the depth.

Coplanar surface calibration, with both loops lying on the surface, is possible, but is restricted to short spacing (perhaps 30-50 metres) as the ground has more effect on the signal than in the coaxial arrangement. Remember that the received signal strength is exactly one half that obtained with the coaxial arrangement.

Depth by Ratiometric Methods

Ratiometric depth measurement is perhaps the simplest method overall with no calibration or angle measurements required (Gibson, 1995, 1996). Once at ground-zero (precise location is not essential) one simply records the field strength, V_1, with the receive loop horizontal then raises the loop a known height, H, (5% of expected depth is a good minimum) and records the strength again, V_2. Since it is not necessary to adjust the receiver's gain between readings, and only the ratio of the numbers is used, no calibration is required. The rf amplifier must not be overloaded and the beacon signal must remain constant for accurate results. The calculation is a variation of the free-space cubic fall-off equation:

$$D = \frac{H}{\left(\sqrt[3]{\frac{V_1}{V_2}}\right) - 1}$$

The conductivity of the rock will cause errors in all three of the depth measurement techniques, but good results should be obtained up to a depth of 30-60 metres with any of the methods. In homogeneous (uniform) earth, the null-angle and ratiometric methods should always give a value *less* than the actual depth, while the field-strength method should always give a value *greater* than the actual depth. As depth increases, the spread between the absolute and ratiometric methods will increase, but the actual depth should always lie between them! At great depths the average of the two values will be closer to the actual depth than either value alone. I have successfully simulated these effects by using a computer program that calculates the effect of conductivity on the strength and direction of the beacon's magnetic field (Pease, 1997a). This article describes all three depth methods and quantifies the effect of conductivity. Using two or three methods is also a good way to pick up careless errors, even at shallow depths!

Further Information

Feel free to contact me for any details of construction, calibration, or operation. I also have an idea for improving skirt selectivity which I will try when I build my 874Hz unit. I am also available to do locating work using this gear. My postal address, phone number and e-mail address appear at the end of this article.

Parts List

Resistors

(¼W, 5% carbon film except as noted)

R1, R2, R29, R38, R40	220kΩ
R3, R4 , R25, R27	1MΩ
R5	5kΩ trim pot
R6, R7	47kΩ 1% metal film
R8, R12, R17, R18	10kΩ 1% metal film
R9	5kΩ linear multi-turn pot
R10, R11	100kΩ 1% metal film
R13, R31, R35, R39	10kΩ
R14, R24, R28, R43, R201	100kΩ
R15	1847Ω
R16	720kΩ
R19	5.6kΩ
R20	2MΩ 1% metal film
R21	20.33kΩ (1% metal film trimmed to exact value)
R22	100kΩ (10-turn linear pot with a calibrated dial)
R23, R26, R41, R202	2.2kΩ
R30, R37, R42, R204	1kΩ
R32	9.1MΩ
R33	2kΩ
R34	10kΩ audio taper (i.e. logarithmic) pot
R36	10Ω

Capacitors & Inductors

(All capacitors monolithic ceramic 0.1" spacing, except as noted)

C1, C2	33nF
C3, C4, C5, C22	1μF
C6, C7	10nF
C8, C14, C17, C25, C30, C31, C32, C37, C38, C202	100nF
C9, C15, C16, C28, C33	10μF Tantalum 16V
C13	1nF
C18, C201, C203	160pF
C19	20 to 60pF trimmer
C20	51pF
C21	2μF ceramic (could be two 1μF in parallel)
C23	2.2μF Tantalum 16V
C24	50nF
C26	1μF Tantalum 16V
C27	3.3μF Tantalum 16V
C29	100μF electrolytic
C34	7nF
C35	6.8nF
C36	470pF
L1	270mH shielded (Mouser)

Note:

1. There is no C11 or C12.
2. C34 and C35 are approximate values. They must be varied to resonate.

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